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Renewable energy resources for distributed power generation in Nigeria: A review of the potential

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ABSTRACT

Fossil fuels-based conventional grid extension in developing countries from centralized power systems in urban centres to rural areas is usually capital intensive and in most cases not economically realistic. From a global perspective, more than a quarter of the human population experiences an energy crisis, especially those living in the rural areas of developing countries. Among these numerous victims of global energy shortage are the majority of people in sub-Saharan Africa, like Nigeria. More than 80% of Nigerians consistently rely on combustible biomass especially from forest wood and its charcoal derivatives for primary energy consumption amidst a serious shortage of access to modern energy sources. Nigeria has abundant renewable and non-renewable energy resources. While most attention is concentrated on tapping only the traditional bioenergy resources, other renewable energy resources are underexploited. This article reviews comprehensively the potential of four major kinds of renewable energy sources (biomass, solar, wind and hydro) in Nigeria. A total energy potential of 697.15 TJ is estimated from crop residue, 455.80 PJ from animal waste and 442 MW from municipal solid waste in Lagos metropolis alone. The solar radiation in the country ranges from 4 kW h/m^2 in the south to 7 kW h/m^2 in the north, which is sufficiently above the threshold average value of 2.3 kW h/m^2 required for the operation of simple domestic load especially in rural communities. Wind speed in the country varies from 1 m/s in the southern plain to 7.96 m/s far northwest in Katsina State between June and September. Unexploitable hydropower potential of 12,954.2 MW also exists as against the backdrop of 10,000 MW required to raise the socio-economic growth level and alleviate poverty in the country.

Contents

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1. Introduction

The objectives of harnessing renewable energy (RE) in developing countries are to focus on provision of sustainable energy to the economically subjugated fraction of the society, combat energy shortage, encourage the development of rural infrastructure and provide clean energy from the perspective of the Kyoto directive towards global decarbonization. This concept of RE has become a fast growing idea in the global power sector. The popularity of RE development can be directly allied to the growing trend of environmental concern and the rapidly depleting reserves of conventional energy resources due to the aggressive utilisation. These emergent concerns call for a viable alternative solution to the contemporary environmental challenges and the energy crisis scenario through sustainable means. There is increasing struggle in the developed and developing countries to make provision for essential services such as electricity to humanity through sustainable development. Sustainable development is a goal that many countries all over the world aspire to achieve [1] to preserve the environment and achieve economic and social development. Realistically, the developing countries of South Asia and sub-Saharan Africa (SSA) are well-known for their over-dependence on traditional energy sources due to poor technological access. However, to achieve sustainable development, there must be an adequate transition to the emerging energy technologies. Nigeria is the most populous country in Africa with over 160 million people but has very limited access to electricity compared to some countries even in SSA despite the presence of huge oil, gas and other energy resources.

Poor access to energy in the country obviously translates into increased poverty, poor economic performance, limited employment opportunity and complicated prospects for institutional development. The high growth rate of the population is an indication that the country's energy demand will continue to rise, similar to how the increase in global population and industrial transformation of the 20th century tremendously increased energy demand [2,3]. The energy crisis situation in Nigeria has considerably affected the public users of electricity. This phenomenon has undeniably compelled the majority of households in both rural and urban segments of the country to significantly depend on combustible RE sources especially for domestic heating and cooking. Fuel wood and charcoal are widespread energy sources commonly used in Nigeria and across SSA. Conventional biomass consumption has received little attention in the ongoing biofuel debate, because it is considered unsustainable and primitive [4]. Fig. 1 shows that more of the fuel consumed in Nigeria in 2007 is obtained from fuel wood and kerosene with fuel wood alone running to approximately 70%. Fuel wood is predominantly used by those without the potential to meet the expense of commercial alternatives [5–23]. A share of electricity consumed was just 0.52% within the same time period. The diminishing access to electricity arising from inadequate supply has resulted in the depletion of the natural biodiversity, human health deterioration, continuous deforestation and land degradation through excessive cutting of trees for domestic energy consumption.

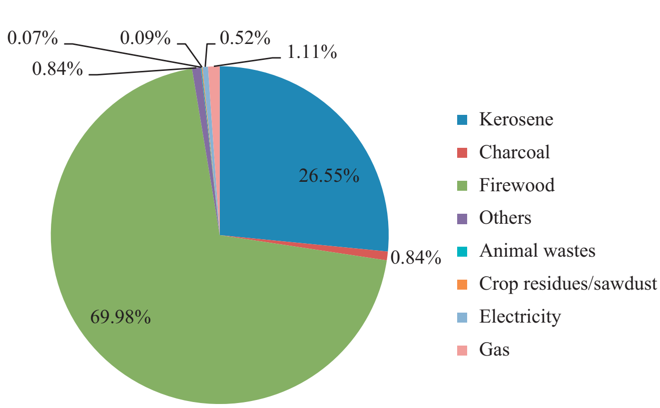

Fig. 1. Shares of energy consumption by source in Nigeria [24].

There are several other renewable energy resources (RES) in the country such as wind and solar, which are yet to be exploited. The Nigerian hydropower development is very limited compared to its exploitable potential. The development of solar energy is highly restricted to a few individual homes in urban cities and some public street lighting operations to augment power shortage from the public utility grid. Though there is vast research on the potential of wind power in Nigeria, its development has not attracted attention. This article critically reviews the current potential of RES in Nigeria as well as policy issues and challenges towards decentralized RE generation.

2. Nigerian power sector and its looming crisis

Nigeria is naturally endowed with diverse and sustainable renewable and non-renewable energy resources. The main RES in the country are biomass, wind, solar and hydro with different degrees of sustainable potential. A reserve crude oil deposit of as much as 36 billion barrels and natural gas 187.44 trillion cubic feet was estimated in 2005 (Table 1). Nigeria, being a key member of the Organization of Petroleum Exporting Countries (OPEC), is one of the major oil exporters in the world market today and is ranked the eighth largest producer [25,26].

Table 1
Nigerian energy reserve and capacity (2005) [27].

Source of energy	Estimated reserve
Crude oil	36.5 billion barrels
Natural gas	187.44 trillion cubic feet
Tar sands	30 billion barrels of oil equivalent
Coal and lignite	Over 40 billion tonnes
Large hydropower	11,235 MW
Small hydropower	3500 MW
Fuel wood	13,071,464 ha
Animal wastes	61 million tonnes/yr
Crop residues	83 million tonnes/yr
Solar radiation	3.5–7.5 kW h/m^2/day
Wind	2–4 m/s at 10 m height

Table 2
Energy generation (MW h) by power stations in Nigeria, 2007–2008 [4].

Power station	2007	(%) of total	2008	(%) of total
Kainji	2816,749.70	12.26	2,707,020.00	12.90
Jebba	2750,325.00	11.97	2,794,976.00	13.32
Shiroro	2230,768.00	9.71	2,089,460.00	9.96
Egbin	3636,680.52	15.83	4,528,451.09	21.58
AES	1552,586.28	6.76	1,846,704.40	8.80
Omotosho	147,541.60	0.64	491,324.90	2.34
Afam	1401,159.60	6.10	300,209.60	1.43
Okpai	3294,207.00	14.34	2,708,690.80	12.91
Sapele	490,290	2.13	728,977.00	3.47
Delta	2696,718.60	11.74	1,510,988.00	7.20
Ajaokuta	357,110.00	1.55	995,873.98	4.75
Geregu	1208,341.20	5.26	N/A	N/A
Omoku	348,583.54	1.52	211,752.37	1.01
Rivers	9,976.00	0.04	42,960.00	0.20
NESCO	37,092.16	0.16	23,390.82	0.11
Total	**22,978,128.66**	**100.00**	**20,980,778.96**	**100.00**

Even with the existence of these substantial energy resources, the nation is deep-rooted in a serious energy crisis. The energy delivery infrastructure is absolutely inadequate to handle the energy demand of the country. Only about 40% of the households in Nigeria have access to the public utility supply [28] and only 46% have access to electricity [29]. Moreover, efforts towards considerable expansion in the quantity of electric power generated are not simultaneously accompanied by tactical expansion of the transmission and distribution systems. This is mainly prevalent in rural areas where the government focuses on traditional grid extension for electricity provisioning without any corresponding expansion of the generation system. Only 2% of the rural households in Nigeria have access to electricity either by rural electrification actions initiated by the government or self generation by private individuals [30].

There has been a consistent drop in power production from the nation's power sector due to inadequate funding, persistent economic regression, poor system maintenance strategies and constraints of technical reliability. A drop of 8.69% is observed between 2007 and 2008 (Table 2). The gross energy output of Kainji, Jebba, Shiroro, Egbin, Ajaokuta, Sapele, Omotosho and AES increased whereas that of Geregu was unavailable due to a shortage of gas supply resulting from the Niger Delta crisis. NESCO is a privately owned hydroelectric utility company operating in Jos, a city in North Central Nigeria. Affected by the incessant sectional crisis in the state, it delivered the lowest energy output in 2008. The 'Electric Power Sector Reform' (EPSR) Act of 2005 was passed to bring about the much needed reforms into the energy sector. The main focus of the Act was to ensure that the electricity sector went through noteworthy changes within a short to medium time period [31–33]. The reality is that the theoretical reforms lacked implementation strategy. The overall situation of the nation's power sector can be described as one of sporadic power failures and characteristic severe state- and district-wise load shedding.

3. Review of related literature on RE potential for distributed generation implementation in SSA

Research on the potential of RE resources has gained importance in this era of pursuit for sustainable energy development. A greater portion of Africa, especially SSA, has a large fraction of the population with no access to modern electricity (Fig. 2) [34,35]. The ongoing power sector reforms in Africa [36] strongly envisage the need for the estimation of different kinds of energy resources in the region. Thus, SSA countries have found it to be a worthy task to independently estimate the potential of their RE resources as they have more energy demand from rural and remote areas, which dominate the land area. The regional hydroenergy and geothermal potentials are estimated to be 1800 TW h [37] and 14,000 MW, respectively [38]. Further, there is also a high potential of power generation from solar radiation [39,40] and biomass [41–43]. Biomass has an estimated potential of 15,000 MW from just 30% of residues from agricultural crops and forest logging residues [29].

There is a vast literature regarding RE implementation based on the distributed generation concept in many countries of SSA. Kiplagat et al. [44] studied RE in Kenya with the focus on the potential for exploitation as well as the status of development. The study concluded that vast potential for power generation using bagasse and biogas exists coupled with substantial biofuel production capacity. Abanda [45] conducted a study on RE potential, benefits and environmental sustainability in Cameroon and concluded that the country has a realistic potential for renewable electricity development with biomass and solar energy on the leading edge. Wind energy is viable in selected regions of the country whereas the actual potential from geothermal and tidal sources is yet to be ascertained. In Ghana, the potential of agricultural biomass for decentralized energy in rural and remote settlements of the country was investigated [46]. The study indicated that there is huge potential for electricity generation using a variety of bio-residues produced in the country.

Tiam [47] reviewed an article with respect to RE decentralized electricity in a microgrid project in Senegal. A feasibility analysis based on solar and wind energy stand-alone systems was the focal point. The findings point to the potential of producing electricity from solar power and wind. Maiga et al. [48] studied the RE options for the Sahel African region, with a specific reference to Mali. The analysis indicated that Mali, though an economically challenged nation, has the potential for RE exploitation. It was concluded that the exploitation and utilization of RE in the country could combat poverty, poor energy access and threatening desertification. The potential of RE in South Africa has been critically reviewed [49]. The country is found to be endowed with RE sources particularly solar radiation. It is suggested that RE

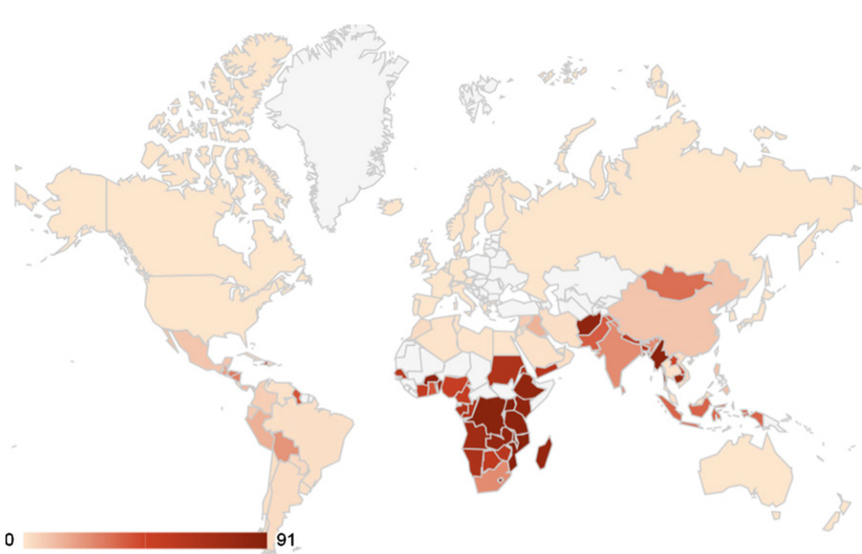

Fig. 2. Percentage of population with no access to electricity [34–35].

deployment in the country could possibly confront a number of challenges affecting the development plan of action especially in the rural areas.

Nigeria being in the same sub-Saharan region and deep-rooted in energy crisis like the countries mentioned here with the exception of South Africa should not be left behind in the expedition for potential assessment of RE resources. This is very crucial for both the present and future energy planning. Invariably, to widen the socio-economic status of developing countries, more access to modern energy has to be created; therefore, effectual knowledge on the types and quantities of RE resources available is imperative to influence national policy makers' decision, stakeholders' interest in energy investment and to refine the government's approach and priority towards RE development.

4. Renewable energy resources with potential for power generation in Nigeria

4.1. Biomass power sources

Biomass is the third largest primary energy resource in the world after coal and oil [50]. Biomass is all biological plant and animal matter that can be used for energy production. It comprises four major categories—agricultural source, forests and their derivatives, municipal solid wastes and animal dung. Bioenergy resources can be converted to heat, electricity or biofuel

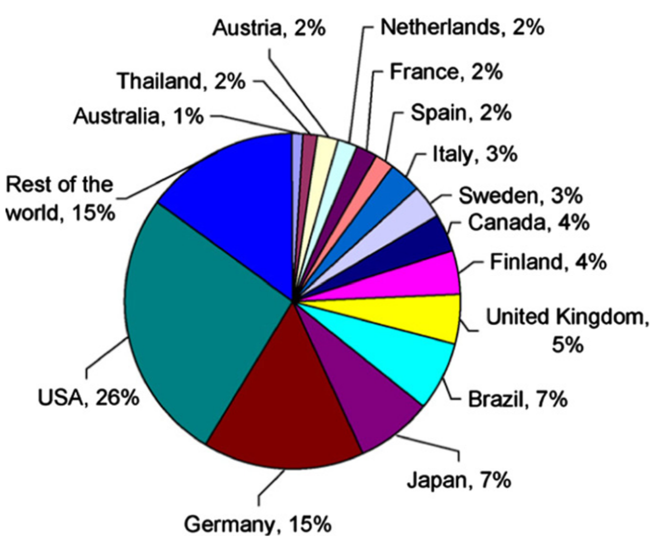

Fig. 3. Global distribution of biomass energy consumption in 2008 [52].

through different modern technologies that can guarantee better efficiencies and reduce atmospheric pollution. Biomass is the oldest form of energy and is used by humans since prehistoric eras though in traditional forms. Biomass has been a traditional source of primary energy for the majority of people in Africa. Globally, application of biomass for electricity has progressively increased by an average of 13 TW h annually between 2000 and 2008 [51]. In the last few years, more developed and developing nations have favoured the development of biomass for power generation. This has created a widespread recognition for biomass among other RES as shown in Fig. 3 with the United States of America leading the trend. There are numerous sustainable renewable bioenergy resources in Nigeria for power generation.

4.1.1. Agricultural residue

Agricultural residue production in Nigeria is dictated by ecological zones and regional agricultural activities. Nigeria is a developing agrarian nation where agriculture basically supports the rural microeconomics but the national economic index rests on crude oil export, which accounts for more than 85% of the country's revenue. About 80% of the country's total land is cultivable and typically supports cereal crop production. The most important source of agricultural residue in Nigeria is cereal crop residue. The crops are essentially consumed as staple feedstock in the country and during the harvest season, large quantities of processing residue are generated. Most of the residue is burnt in the farm to allow for further cultivation of the soil. This destruction becomes inevitable due to an inability to utilize the residue for modern energy production. At the household level especially in rural communities, a part of the residue is used for domestic fuel by direct burning in traditional three-stone stoves. In urban settlements, the agricultural residue generated is discarded as part of the municipal solid waste. Table 3 summarises the energy potential of different agricultural residues in the country.

Apart from cereal crop residue, there are other agricultural biomass sources namely *Jatropha curcas*, sunflower, cassava, sugarcane and castor oil with sustainable potential for liquid biofuel production. Considering the fact that Nigeria has a sustainable potential for biofuel production, the Federal Government of Nigeria gave a directive for biofuel production in the country in 2005 to the Nigerian National Petroleum Corporation (NNPC) to initiate the development of biofuel for automotive consumption [58]. Through the pursuit of RES for diversification and consolidation of local investment, biofuel development has the potential to alleviate poverty in Nigeria. The use of biofuels enhances the potential for the Nigerian economic [59] growth. There is a hopeful trend in the prospect for biofuel development

Table 3
Energy potential of major agricultural residues in Nigeria based on 2010 FAO statistics..

Agricultural crop	Generated residue	Production quantity (10^3 t)[a]	Crop to residue ratio (PRR)	Calculated residue generated	Energy content (MJ/kg)	Energy potential (TJ)
Maize	Stalk	7306	1.5 [53–54]	10,959	15.48 [56]	169.65
Rice, paddy	Straw	3219	1.5 [53–54]	4,829	15.56 [56]	75.14
Sorghum	Stalk	4784	2.62 [53–54]	12,534	17.00 [56]	213.08
Wheat	Stalk	34.2	1.5 [55]	51.3	19.3 [56]	0.99
Coconut	Shell	170	0.6 [53,54]	102	10.61 [56]	1.08
Oil palm fruit	Empty fruit bunch	8500	0.25 [53,54]	2,125	15.51 [56]	32.96
Sugarcane	Bagasse	1414	0.3 [53–54]	424.3	13.38 [56]	5.68
Cocoa	Husk	428	1.0 [53,54]	428	15.48 [56]	6.63
Millet	Stalk	4125	3.0 [53–54]	12,375	15.51 [56]	191.94
Total						697.15

[a] Crop production quantity data [57].

in Nigeria especially in bio-ethanol production due to an increasing number of companies showing interest in the investment. The existing biofuel companies are also expanding their production capacities. Presently, prominent companies involved in bio-ethanol production are Alconi/Nosak (43.8 million l/year), UNI-KEM (65.7 million l/year), Intercontinental Distilleries (9.1 million l/year), Dura clean (4.4 million l/year) and Allied Atlantic Distilleries Ltd. (10.9 million l/year). The Nigerian Yeast and Alcohol Manufacturing Company is currently building a $200 million ethanol manufacturing plant with a capacity of 30 million l/year.

4.1.2. Municipal solid waste

Municipal solid wastes (MSW) are materials generated from the daily activities of humans. Municipal solid waste management in Nigeria includes both open dump in unmanaged sites and controlled sanitary landfills. Organized sanitary landfills are limited to major urban cities like Abuja, Lagos, Ibadan, Akure and other state capitals. The average municipal solid waste per capita per day significantly varied from place to place in Nigeria, for example Lagos (0.63 kg), Kano (0.56 kg), Ibadan (0.51 kg), Kaduna (0.58 kg), Port Harcourt (0.60 kg) and Onitsha (0.53 kg) [60]. The value appreciably varied in different places depending on the economic activities, social standard of living and level of urbanization. Municipal solid waste mostly contains two basic components of biodegradable and non-biodegradable matter. The biodegradable fraction can be treated by anaerobic digestion for biogas, a highly combustible gas used for cooking and power generation.

Many developing countries have been promoting biogas consumption due to its clean nature for considerable emissions reduction. In 2005, it was reported that 17 million households used biogas in China, 3.8 million in India and 170,000 digesters were installed in Nepal [61,62]. Biogas production technology offers another advantage of good fertilizer as a by-product [63,64]. Apart from these benefits, both the organic and inorganic fractions of MSW can also be used for electricity generation by thermo-chemical conversion in an incineration or gasification power plant. A sustainable potential of approximately 442 MW was estimated for Lagos metropolis (Table 4). Besides, other densely populated and economic nucleus cities in the country like Port-Harcourt, Kano and Kaduna could have better potential for power generation using MSW. A 35 kW electricity project has been initiated in Bodija (Oyo State) to utilize biogas from abattoir waste generated in the area. Often, environmental reports on municipal abattoirs raise issues concerning the spread of disease-causing microbes such salmonella, Rift Valley fever virus and *Escherichia coli* bacteria especially if the wastes are let out into open systems. This validates the need to capture the waste for constructive development and environmental sanitation.

Table 4
Estimated power generation potential from MSW in Lagos Metropolis [65].

Local Government Area	Estimated power generation potential (MW)
Agege	28.5
Ajeromi-Ifelodun	37.7
Alimosho	56.5
Amuwo-Odofin	14.5
Apapa	14.5
Eti-Osa	27.2
Ifako-Ijaiye	20.6
Ikeja	17.9
Kosofe	25.8
Lagos Island	23.8
Lagos Mainland	17.4
Mushin	36.5
Ojo	26.0
Oshodi-Isolo	31.3
Somolu	28.3
Surulere	35.2
Total	**441.7**

The potential of MSW can be exploited for power generation as a smart option for clean development mechanism. In most Nigerian cities, the recyclable parts in the MSW are collected by human scavengers from open dump areas. Contrarily, in advanced countries, recyclable materials from MSW are separated by machines before the MSW is taken for landfilling or power generation. This is done to prevent any hazardous encounters as MSW is a major source of uncontrolled biogenic waste emissions like methane, carbon dioxide, ammonia and nitrous oxides.

4.1.3. Forest biomass

The exact potential of forest biomass in the country is not well known due to poor record keeping of forest resource production and exploitation. The trees, residues and charcoal derivatives are mainly consumed as combustible biomass. The soaring reliance on traditional biomass for energy is revealed by the fact that 80% of the wood harvested in developing countries is used for fuel wood consumption [66–68] and the value is about 90% for Africa [61]. In the last few decades, a great fraction of the country's forest resources has been ruined. The harvested forest trees are mostly used for fuel wood, charcoal, plywood and timber production. However, it was estimated that 12% of the total land mass of the country is covered with forest and wood (Fig. 4). Forest biomass in Nigeria varied from north to south. The forest in the northern part of the country is highly open structured and dominated by wood and shrubs. In the southern part, thick rain forest trees are found. As a measure to counter rapid deforestation, most forest developers are now planting short rotation trees such as *Gmelina arborea, Gliricidia sepium and Leucaena leucophala* particularly in Southern Nigeria.

About 95% of the established forests in Nigeria are owned by the government. Undisputedly, these forest lands are not well secured for their resource conservation because private individuals can easily encroach into the forest for firewood extraction. In addition, most lumbering activities are not regulated as a result of loose control and weak forest policy and implementation strategy. Excessive harvest of forest and shrub land wood resources for bioenergy is also a great limiting factor affecting the establishment of new natural and planted forest areas. Bush lands are usually ransacked by women for firewood irrespective of the state of succession of the plants. This is predominant among rural inhabitants with limited access to forest wood and less financial capability to obtain alternative energy through electricity or kerosene. This continuous harvesting pressure has resulted in an increase in the quantity of fuel wood and charcoal production as shown in Figs. 5 and 6 [70], respectively. Fuel wood and charcoal are widely used by the economically and socially less privileged people. A majority of the fuel wood consumers are not aware of the environmental consequences of the excessive extraction [71].

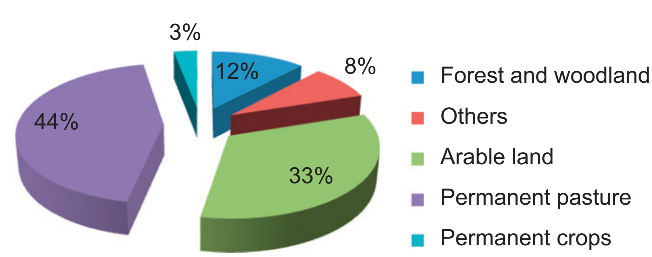

Fig. 4. Percentage estimate of land use in Nigeria [69].

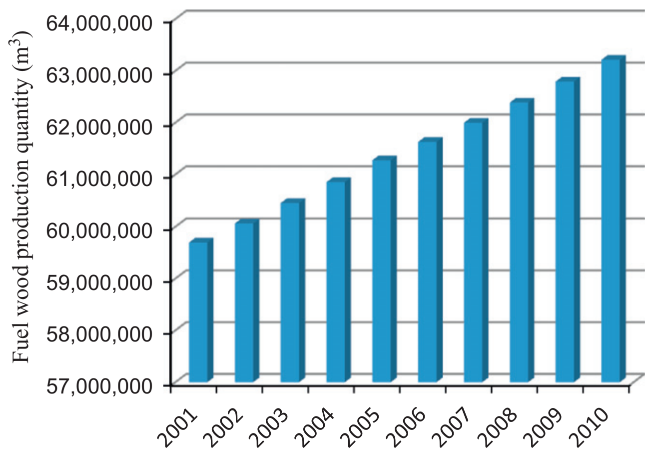

Fig. 5. Fuel wood production from 2001 to 2010 [70].

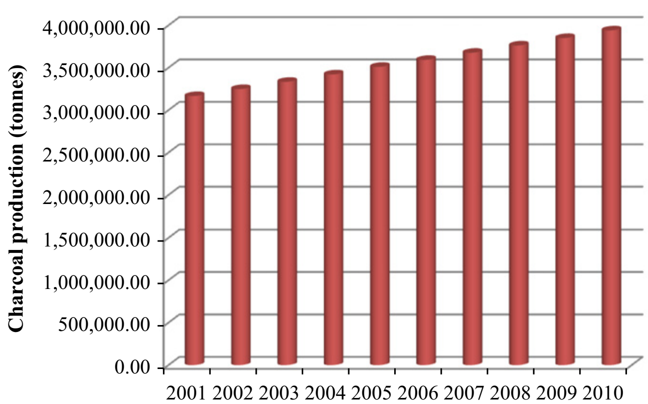

Fig. 6. Charcoal production from 2001 to 2010 [70].

Table 5
Livestock production quantity in Nigeria from 2001 to 2010 [74].

Year	Cattle	Pigs	Goats	Sheep	Chicken
2001	15,133,400	5249,540	45,260,400	28,692,600	124,620,000
2002	15,148,600	6111,820	46,640,000	29,400,000	131,125,000
2003	15,163,700	5677,900	47,551,700	30,086,400	137,680,000
2004	15,700,000	5910,000	48,700,000	30,800,000	143,500,000
2005	15,875,300	6141,220	49,959,000	31,547,900	150,700,000
2006	16,065,800	6390,000	51,223,600	32,314,200	158,400,000
2007	16,152,700	6642,340	52,488,200	33,080,300	166,127,000
2008	16,293,200	6908,030	53,800,400	33,874,300	174,434,000
2009	16,435,000	7184,360	55,145,400	34,687,300	183,156,000
2010	16,578,000	7471,730	56,524,100	33,519,800	192,313,000

4.1.4. Animal residue

Animal residue is another major source of RE in the country. This consists of livestock residue more precisely referred to as animal dung. Cattle, pigs, goats, poultry (turkey, chicken and duck) and sheep are the main livestock reared in Nigeria. Production of animal dung varies across different animal species depending on factors such as animal body size, frequency and quantity of feedings and animal head counts. The northern regions of Nigeria harbour most of the nation's ruminant livestock [72], especially cattle. The FAO statistic for animal production is presented in Table 5. In 2010, estimated populations of livestock were 16,578,000 (cattle), 7471,730 (pigs), 56,524,100 (goats), 33,519,800 (sheep) and 192,313,000 (chicken). The dry dung output in kilograms per head per day are 1.8 (cattle), 0.4 (sheep), 0.8 (pigs), 0.4 (goats) and 0.06 (chicken) [73]. Using energy values of 18.5 GJ/t (cattle), 14.0 GJ/t (sheep), 11.0 GJ/t (pigs), 14.0 GJ/t (goats) and 11.0 GJ/t (chicken) [73], these correspond to energy potentials of 201.5 PJ, 68.5 PJ, 24.0 PJ, 115.5 PJ and 46.3 PJ, respectively.

Animal manure is another feedstock most suitable for biogas production by anaerobic digestion similar to the organic fraction of MSW. It can also be used as a co-substrate with human waste or other wastes for biogas production especially in a centralized anaerobic digestion (CAD) facility. In CAD, the feedstock used are predominantly manure and industrial biogenic waste [75]. The possibility of biogas production through CAD seems sustainable in the northern part of the country, which has the largest share of the nation's livestock population. A majority of rural community in the northeast and northwestern parts directly depend on livestock farming as a basic source of livelihood.

Though the livestock rearing system in Nigeria is predominantly free-roaming, but the animals are kept in seclusion at night, which can still make it easy for the waste collection. Till date, less than 10 biogas digesters have been installed including in a prison in Zaria, National Animal Production Research Institute (NAPRI), Zaria, Ojokoro/Ifelodun, Lagos and Mayflower Secondary School, Ikene, Lagos. A majority of the large farm livestock owners are ignorant of the importance of biogas production from animal manure.

4.2. Solar power

The intensity of solar radiation exhibits remarkable variation from the north to the south of Nigeria (Fig. 7) but is dependably higher in the northeastern axis. Nevertheless, the entire country has enough solar radiation to sustain the domestic local energy requirement especially in rural areas with smaller electrical load demand. Using the benchmark of 2324 W h/m^2/day as the average domestic load demand [76], Nigeria has a solar radiation potential ranging from 7000 W h/m^2 in the farthest northeast to 4000 W h/m^2 towards the end of the southern belt of the country (Fig. 7). A unique tendency of solar energy is that it is available in every part of the world. The potential of solar as a renewable source of energy is apparently limitless [77]. Solar energy is captured on reaching the earth's surface and based on the fact that the temperature of a radiating body is greater than absolute zero, the heat energy generated can be converted to electrical energy. Many studies have been conducted on the potential analysis of solar energy application in Nigeria and virtually all indicated that vast opportunities for tapping solar energy existed.

Fig. 8 is a representation of the solar photovoltaic potential for some selected cities in different geopolitical zones of the country, namely Port-Harcourt (South–South), Owerri (Southeast), Lagos (Southwest), Abuja (North Central), Sokoto (Northwest) and Maiduguri (Northeast). Maiduguri exhibits the highest potential value of solar photovoltaic while Sokoto is the second highest. Abuja, the Federal Capital Territory located in the North Central shows remarkable potential with a minimum value greater than 3000 W h/m^2/day. In the southern axis, Port-Harcourt displays the least potential in July but still maintains a value higher than the threshold. Generally, the period June–August experiences a notable fall in potential due to high cloud cover resulting from peak rainy season.

Efforts towards harnessing solar energy in Nigeria have been championed by the Energy Commission of Nigeria (ECN) through direct coordination of research and development activities of Sokoto Energy Research Centre (SERC) and National Centre for Energy Research and Development (NCERD). By this arrangement, solar based PV-connected rural electrification of schools, cottage hospitals, urban traffic lighting, water pumping, domestic lighting and small-scale laboratory applications have been established.

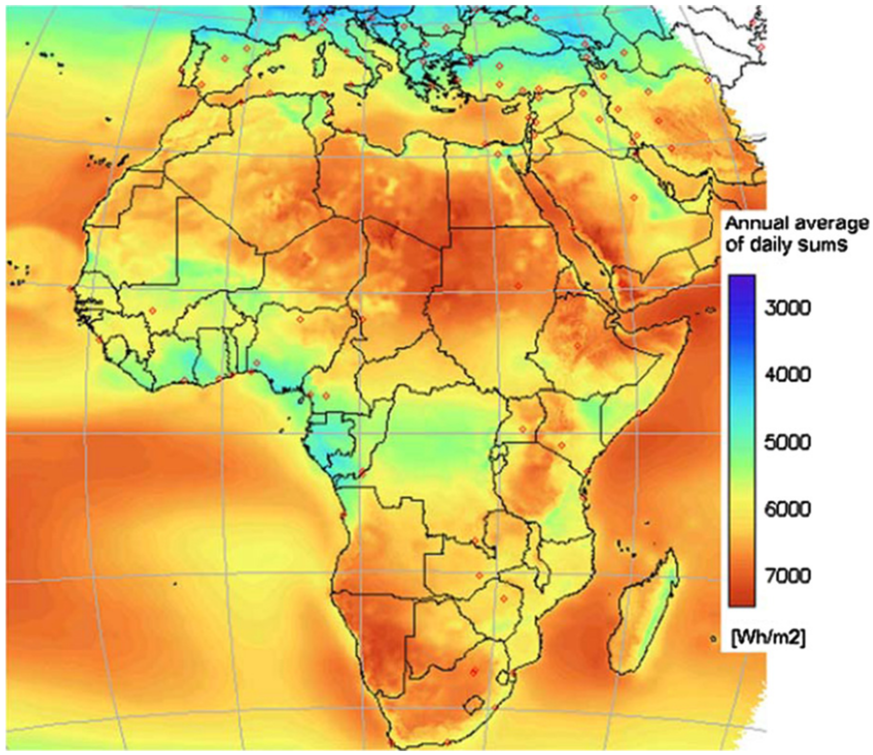

Fig. 7. Annual average of daily sums of solar irradiation for Africa [78].

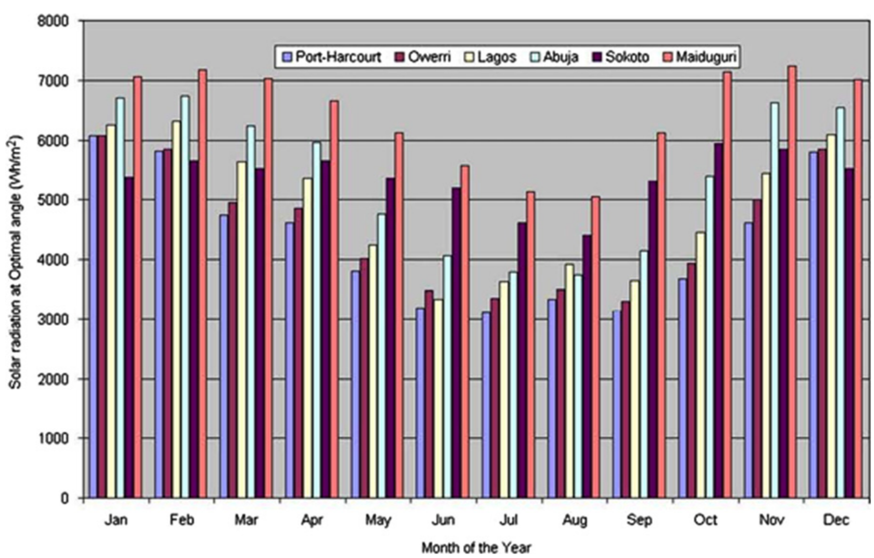

Fig. 8. Solar photovoltaic potential for some selected cities in Nigeria [78].

The global power sector has generally exhibited a growth rate of 2% per annum with RE consumption of about 25% on a yearly basis, with an estimated 50% of solar energy alone [79]. This development in solar energy has resulted in an increase in access to energy and creates employment for numerous job seekers in developing countries.

4.3. Wind power

Wind is another important source of clean and RE with the ability to be used for power generation where available. In different parts of the world and especially in Europe, America and some parts of Asia, wind energy systems have been used to reduce the environmental constraint from fossil based power generation. Wind power is usually harnessed through the mechanical power generated by aero-turbines located at a suitable position usually referred to as wind farm. A hybrid power system comprising wind and solar has been used successfully as well. Realistically, the success of wind energy development in the country depends on the intended promotional strategies by ECN, which has been the key player behind energy research and potential evaluation in the country. Applications of wind for power generation have been the least diffuse among the renewable sources of energy in Nigeria due to poor awareness and lack of support from the government. Based on the projection by [80], wind shows a superior contribution to electricity generation in

the country both at 7% and 13% growth rates (Table 6). Presently, the utilization of wind power in the country is only limited to a few water pumping operations, and many of these too have been abandoned. Apart from the 5 kW wind power generation system in Sokoto state (Sayyan Gidan Gada), the other systems in northern Nigeria are not in use. Several research studies have been undertaken to determine the potential of wind application for power generation in the country. The common conclusion is that the potential of wind in the country varies from weak to modest category.

It was reported [28] that an annual mean speed of not less than 5 m/s at an altitude of 10 m above the ground is the satisfactory speed for the utilization of wind power based on present day cost scenarios. Fig. 9 displays four different wind speed regimes with increasing effects in strength from the southern coast to the far north. Mean wind speed is the main parameter that determines the capacity to exploit any advantage offered by wind resources for power generation. A more recent study [81] revealed that wind speed potential in some parts of the country in the north appreciably met the 5 m/s requirement for wind power generation (Table 7). Gusau, Katsina and Kano met the requirement in both rainy and dry seasons whereas in the dry season, all the study sites met the benchmarked speed. In the rainy season, values above 4 m/s were recorded for Kaduna, Bauchi and Potiskum, where Potiskum recorded the least potential. Further, Kano and Katsina show an all-time high potential in both rainy and dry seasons. In these study sites, the wind energy has not been exploited but < 1 kW wind power systems were established in Katsina (Goronyo) and Bauchi (Kedada). These were later abandoned as the rural communities had neither the financial strength nor the human intellectual capacity to adequately maintain the systems.

Table 6
Projected electricity production by fuel-mix for 7% and 13% growth rates [80].

Year	7%				13%			
	Hydro	Small hydro	Solar	Wind	Hydro	Small hydro	Solar	Wind
2010	3,702	40	5	0	3,702	208	30	500
2015	4,962	90	10	126	4,962	360	80	1,200
2020	6,479	140	34	1471	6,479	1000	750	3,971
2025	9,479	227	75	3019	9,479	1956	2670	6,920
2030	11,479	701	302	5369	11,479	2353	4610	15,567

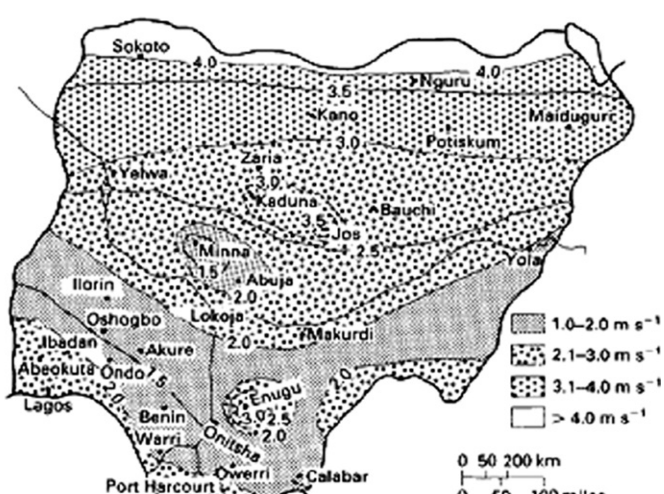

Fig. 9. Annual mean wind speed distribution in Nigeria (isovents at 10 m height) [82].

Table 7
Seasonal variations of wind characteristics for six sites in Nigeria from 1971 to 2007 [81].

Location/season	Mean wind speed (m/s) at 10 m height	Average power density (W/m^2)	Monthly seasonal duration range
Gusau			
Rainy season	5.45	120.83	June–September
Dry season	6.42	207.31	October–May
Kaduna			
Rainy season	4.78	74.61	June–September
Dry season	5.52	126.70	October–May
Katsina			
Rainy season	7.96	391.31	June–September
Dry season	7.19	314.13	October–May
Kano			
Rainy season	7.81	371.03	June–September
Dry season	7.74	367.86	October–May
Bauchi			
Rainy season	4.39	80.37	June–September
Dry season	5.16	149.17	October–May
Potiskum			
Rainy season	4.02	46.21	June–September
Dry season	5.20	89.57	October–May

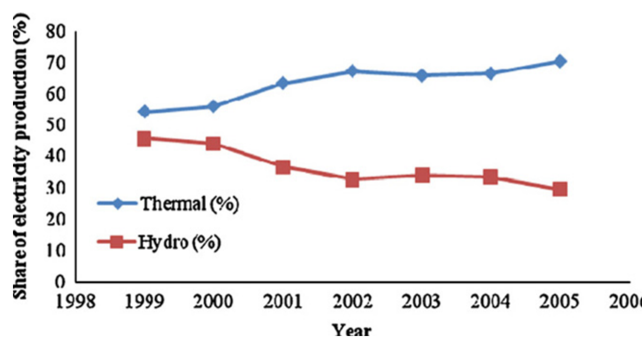

Fig. 10. Percentage contribution of thermal and hydro to electricity supply in Nigeria 1999–2005 [83].

4.4. Hydro power

Hydroelectric power resource in Nigeria was first tapped in 1962 by the Niger Dams Authority (NDA). Hydropower generation in Nigeria has substantial potential including the small, mini and micro water capacity for power generation but in the last few years its total power contribution has significantly declined due to some technical reasons (Fig. 10). The discovery of oil and gas and subsequent application of natural gas for power generation has without a doubt greatly affected the hydropower development in Nigeria. The installed capacity of the hydropower plants in Nigeria has remained stagnant for many years while the output power produced has continued to decline due to lack of proper maintenance and seasonal fluctuations in the volume of water flowing into the reservoirs. Nigeria has three hydropower sites: Kainji (760 MW), Jebba (540 MW) and Shiroro (600 MW). The fourth hydropower station, owned by a private utility service company, the Nigerian Electricity Supply Corporation Limited (NESCO), is located at six different sites in Plateau State but has a total potential of just 21 MW.

The country's hydropower potential is underexploited despite its vital role in the electric power generation in the global energy sector. Hydropower as one of the foremost RE sources contributes more than 97% of the total electricity from renewable resources and approximately 22% of the electricity generated globally [84,85]. Different categories of hydropower such as large, small, mini and micro exist in Nigeria. Several studies conducted on the potential evaluation of exploitable hydropower in the country revealed that small hydropower (SHP) with capacity of less than

10 MW is more prevalent. Small hydropower has been favorably used in many parts of the world due to its optimal civil construction expenses and limited environmental destruction in the form of land used for dam construction. Tables 8 and 9 present a total sum of 764.2 MW of SHP from 286 sites spread across different locations in the country. Only 30 MW of this potential is currently in existence as indicated in Table 9, while the remaining 734.2 MW is yet to be exploited.

The Nigerian landmass, especially the northern part with a hilly landscape coupled with the presence of waterfalls, natural dams and natural streams located at a height above ground level, is suitable for hydropower exploitation. Many water bodies were impounded by dams but most of them are used for fishing and recreation after being abandoned by the government. Apart from the three large hydropower sites (Jebba, Kainji and Shiroro) already developed, there are still a few large hydropower potential sites recently surveyed (Table 10) by the Power Holding Company of Nigeria (PHCN). In recent times, ECN has focused attention on brainstorming programmes and workshops to cultivate awareness on the importance of RE exploitation, especially SHP, for sustainable development. This has been manifesting in the form of efforts being channeled towards involving international development agencies like the World Bank, United Nations Industrial Development Organization (UNIDO) and United States Agency for International Development (USAID) and including local stakeholders on RE development and application programmes. Still, much is needed to be done locally to overcome some notable challenges for exploitation of any RE energy source for electricity production in the country.

5. Renewable energy development and policy framework in Nigeria

Quite a number of energy policy frameworks have materialized in the past few years to help improve the poor state of energy supply in the country. Increase in population, enthusiasm for modern economic and material transformations as well as human capacity building are activities that need energy to be sustained. The most recent landmark power sector policy reform in the country was passed into law in 2005 following the establishment of a statutory regulatory body; the National Electricity Regulatory Commission (NERC) has been entrusted to coordinate activities in the nation's electricity industry. The policy is called the EPSR Act, 2005. The major idea behind the policy is to break the existing monopolistic context enjoyed by the nation's power sector since its inception in 1962. The outcome of the reforms appears to be partial deregulation as private investors are permitted to procure electricity operating license subject to NERC approval to build, own and operate a power plant.

One of the reform agendas was to unbundle the power sector into three independent companies comprising generation, transmission and distribution, which was realized in 2007. As a consideration for RE exploitation, Rural Electricity Agency (REA) was established to create opportunity for decentralized rural power generation. The operating capacity of REA was to be enhanced with the provision of autonomous funding system through the Renewable Electricity Trust Fund (RETF), which is to be handled by the Rural Electrification Fund (REF). Additionally, ESPR allows private individuals to own and operate a power plant in off-grid mode with a capacity of less than 1 MW without acquiring electricity license from NERC and regardless of the fuel type. This is a strong impetus to RE promotion as in most rural communities of Nigeria, power demand is usually less than 1 MW, which can be generated from renewable sources. It is a mixture of sincerity of purpose, high level of political willingness and

Table 8
Total SHP potential in surveyed states of Nigeria [86].

State	River basin	Total sites	Total capacity (MW)
Sokoto	Sokoto-Rima	22	30.6
Katsina	Sokoto-Rima	11	8.0
Niger	Niger	30	117.6
Kaduna	Niger	19	59.2
Kwara	Niger	12	38.8
Kano	Hadeija–Jama'are	28	46.2
Borno	Chad	28	20.8
Bauchi	Upper Benue	20	42.6
Gongola	Upper Benue	38	162.7
Plateau	Lower Benue	32	110.4
Benue	Lower Benue	19	69.2
Cross River	Cross River	18	258.1
Total		**277**	**734.2**

Table 9
SHP in existence in Nigeria [87].

River	State	Installed capacity (MW)
Bagel I	Plateau	1
Bagel II	Plateau	2
Ouree	Plateau	2
Kura	Plateau	8
Lere	Plateau	4
Lere	Plateau	4
Bakalori	Sokoto	3
Tiga	Kano	9
Total		30

Table 10
PHCN estimate of current exploitable hydropower sites in Nigeria (installed potential) [86].

Location	River	Estimated installed potential capacity (MW)
Donka	Niger	225
Zungeru II	Kaduna	450
Zungeru I	Kaduna	500
Zurubu	Kaduna	20
Gwaram	Jama' are	30
Izon	Gurara	10
Oudi	Mada	40
Kafanchan	Kongum	5
Kura II	Sanga	25
Kura I	Sanga	15
Richa II	Dafo	25
Richa I	Mosari	35
Mistakuku	Kurra	20
Korubo	Gongola	25
Kiri	Gongola	40
Yola	Benue	360
Karamti	Kam	115
Beli	Taraba	240
Garin Dali	Taraba	135
Sarkin Danko	Suntai	45
Gembu	Dongu	130
Kasimbila	Katsina Ala	30
Katsina Ala	Katsina Ala	260
Makurdi	Benue	1,060
Lokoja	Niger	1,950
Onitsha	Niger	1,050
Ifon	Osse	30
Ikom	Cross	730
Afokpo	Cross	180
Atan	Cross	180
Gurara	Gurara	300
Mambila	Danga	3,960
Total		**12,220**

aggressive RE policies that can guarantee effective exploitation of RES for constructive development and poverty alleviation.

As on date, the country is still in need of a market-oriented policy that will increase RE investors' participation in constructive development of the available resources. Effective policy making is an incitement that can strengthen the prospect for investment and development of RE technology. Feed-in tariffs, investment tax credits and renewable portfolios are some policy issues that could be useful to enhance better share of RE in the nation's power generation mix. The suggested issues are regulatory strategies to lower the costs of RE while increasing the adoption of RE sources. With the fact that soaring upfront investment expenses of RE development is sometimes responsible for their being ignored by potential investors, well-structured policies can be employed to resolve issues regarding subsidies and tax waivers. Disciplinary energy experts are convinced that suitable policies and actions are capable of resolving some barriers against RE exploitation [88–91].

6. Challenges towards renewable energy development in Nigeria

There have been some challenges related to the development, diffusion and commercialization of RE for distributed power generation in Nigeria. In many developing countries, electricity supply is not well subsidized due to incessant economic and financial problems. DeLucia [92] stated that renewables might not be exploited to benefit fully from the Kyoto mechanisms due to their economies, small sizes and their dispersed nature. Regardless of the current outstanding progress in RE application in some developing countries, a better level of utilization is possible provided the prevailing constraints to successful exploitation are identified and confronted through proactive policies. It is a well reckoned fact that ascending the energy ladder entails transition from combustible renewables to more effective and cleaner methods of exploitation and diversification of other RE resources in a modern way. The possibility of this transition directly depends on the potential source of income for individuals because as income increases, consumers ascend the energy ladder [93] for cleaner and more comfortable energy sources.

Technological lag, deficient political will, economic uncertainty, poor level of awareness and educational background, financial corruption and bureaucratic ineffectiveness are the key challenges to RE development in Nigeria. Each of these challenges and the convergence of all are the main drawbacks to investment in RE despite the existence of many incentives for exploitation. This has seriously damaged the socio-economic welfare of a majority of the population especially in rural areas. It was reported that about 300 million people have been liberated from poverty attachment in China since 1990 by increasing their access to modern energy [94], which is an indication that there exists an inevitable correlation between energy access and economic growth [95].

7. Conclusion

The preceding sections have established that there is sustainable potential for distributed generation of electricity using RES in the country. Diversification of RES for power generation is an integrated solution to rural energy poverty. Electricity generation from renewables is environmentally friendly as it can be used to offset atmospheric global warming potential from conventional fossil fuels. The potential from hydropower alone estimated in this study is sufficient to keep abreast with the need for economic and industrial development of the country. It can also drastically reduce excessive consumption of firewood and charcoal. There is limited place for electrical energy as a cooking source in developing countries due to high cost. Effective development of other renewables such as biogas from bio-wastes can be used as substitutes at affordable cost. To keep in pace with the high growth rate of the population of Nigeria, RE exploitation to compensate for increase in energy demand especially in rural areas is inevitable. Effective deployment of distributed generation technologies in strategic rural locations where the resources are available can help mitigate the present energy crisis challenges in the country.

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